Deep Infrared Imaging of the Microquasars 1E1740-2942 and GRS 1758-258[1]

S.S. Eikenberry[1,2], W. J. Fischer[1,3], E. Egami[2], S.G. Djorgovski[4]

ABSTRACT

We present deep infrared (2.2μm) imaging of the Galactic microquasars 1E1740-2942 and GRS 1758-258 using the Keck-I 10-meter telescope in June 1998. The observations were taken under excellent seeing conditions ($\sim 0.45''$ full-width half-maximum), making them exceptionally deep for these crowded fields. We used the USNO-A2.0 catalog to astrometrically calibrate the infrared images (along with an optical CCD image in the case of GRS 1758-258), providing independent frame ties to the known radio positions of the objects. For 1E1740-2942, we confirm potential candidates for the microquasar previously identified by Marti et al., and show that none of the objects near the microquasar have varied significantly from 1998 to 1999. For GRS 1758-258, our astrometry indicates a position shifted from previous reports of candidates for the microquasar. We find no candidates inside our 90% confidence radius to a 2σ limiting magnitude of $K_s = 20.3$ mag. We discuss the implications of these results for the nature of the microquasar binary systems.

Subject headings: infrared: stars – Xrays: stars – black hole physics

1. Introduction

The discovery of Galactic relativistic jet systems – the "microquasars" [(Mirabel & Rodríguez 1994); (Tingay et al. 1995)] – promises to revolutionize the study of jets in

[1]Astronomy Department, Cornell University, Ithaca, NY 14853

[2]Physics Department, California Institute of Technology, Pasadena, CA 91125

[3]Ritter Astrophysical Research Center, University of Toledo, Toledo, OH 43606

[4]Astronomy Department, California Institute of Technology, Pasadena, CA 91125

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black hole systems. Due to their proximity and smaller mass, these X-ray binaries reveal smaller/fainter features and vary more rapidly than their extragalactic cousins, the quasars. Thus, patterns of variability which repeat on timescales of decades to centuries for the quasars can be observed on timescales of minutes to days in their Galactic counterparts. This property makes the microquasars excellent test laboratories for investigating the black-hole/relativistic-jet connection.

Based on their X-ray and radio properties, 1E1740-2942 and GRS 1758-258 are both considered strong microquasar candidates (in fact, the term "microquasar" was first used to describe 1E1740-2942). They are the two brightest hard X-ray sources near the Galactic Center at energies > 50 keV, and their hard X-ray tails make them likely black hole candidates (Sunyaev et al. 1991). Furthermore both objects display radio lobes, indicating the presence of collimated jet outflows [(Mirabel et al. 1992); (Rodríguez et al. 1992)]. In their hard X-ray spectra and variability, both objects closely resemble the black hole candidate Cyg X-1 (e.g. Kuznetsov et al. (1996)), suggesting that they may be black-hole/O-star binaries. Both objects lie in the Galactic Plane with high optical obscuration ($A_V \sim 10$ for GRS 1758-258 and $A_V \sim 25 - 50$ for 1E1740-2942), so IR searches for companions/counterparts have been performed. However, initial searches have returned negative results, with upper limits of $K > 17$ (e.g. Djorgovski et al. (1992)), and Mirabel et al. (1991) failed to detect the expected radio emission from the compact HII region an O-star would form.

Recently, faint IR candidate counterparts for both systems have been reported. For GRS 1758-258, Marti et al. (1998) have found 3 obscured optical stars in or near the radio error circle. Similarly, Marti et al. (2000) have reported 1 or more faint IR stars inside the error circle for 1E1740-2942. However, due to the crowded nature of the fields, none of the candidates can be singled out as a certain microquasar counterpart.

In order to identify such counterparts, we obtained deep K_s-band images of both microquasar fields using the Keck 10-m telescope in June 1998. In Section 2, we describe the observations and data reduction we performed. In Section 3, we present our astrometric solutions for the locations of the microquasars on the IR images. In Section 4, we present photometry of the candidate counterparts and limits on potential undetected counterparts. In Section 5, we discuss the implications of these results, and in Section 6 we present our conclusions.

2. Observations and Data Reduction

2.1. Keck IR Observations

2.1.1. June 1998

We observed the fields of both microquasars on June 1-2, 1998 UTC using the Keck Observatory's Near-Infrared Camera (NIRC – Matthews & Soifer (1994)) on the Keck I telescope. NIRC has a 256x256-pixel InSb array with a 0.15 $''$/pixel plate scale, giving a 38$''$ field of view. Due to the high extinction expected given the X-ray absorption towards these objects, we used a K_s filter, centered at 2.15μm. Conditions were not perfectly photometric on either night, with high thin cirrus clouds present, and monitoring of standard stars throughout the observing run indicated that the atmospheric absorption losses were variable at the $\sim$ 10% level. The seeing conditions were exceptionally good, ranging from $\sim 0.35''$ to $\sim 0.55''$, with extended periods of seeing $< 0.5''$.

For both objects, we used a random, non-repeating dither pattern, moving the telescope in 10$''$ steps on the sky around the radio positions of the microquasars. We took 12 coadded 5-second exposures at each position, for a total of 60 seconds on-source per position. We repeated this dithering for a total of 94 minutes of exposure on GRS 1758-258 on June 1 and 99 minutes on June 2. For 1E1740-2942, we obtained 104 minutes of total exposure on each night.

We created a sky background frame by median-combining the dithered images for each object and each night separately. We then subtracted the sky background from each frame, divided by a flatfield created from the dithered sky frame, and interpolated over bad pixels and cosmic ray events. For GRS 1758-258, we then measured the centroid position of several bright stars in each frame and used them to determine its shift relative to a reference frame. We then shifted the frames accordingly and averaged them to obtain a master image of the field of GRS 1758-258 (see Figure 1).

We treated the images of 1E1740-2942 similarly up to the shifting and adding stage. Here the extremely crowded nature of the 1E1740-2942 field necessitated a different procedure. Rather than simply shifting and adding the images, we first measured the full-width half-maximum (FWHM) of the stellar point spread function (PSF) using several bright stars in the field. We then combined the images as above, but rejecting any images with FWHM greater than certain values. We tried several trial values for the FWHM cut, and found that 0.45$''$ FWHM provided the best compromise between good resolution (low FWHM) and total exposure time (high FWHM). We present the resulting master image of 1E1740-2942 in Figure 2.

We also observed the UKIRT photometric standard star FS28. We took five dithered images of this star, which we used to create a sky frame. We subtracted the sky frame, divided by a flatfield, and interpolated over bad pixels and cosmic rays.

2.1.2. April 1994

We also observed 1E1740-2942 using NIRC on Keck I on 5 April 1994. We operated in a very similar mode to that described above, but with a total integration time of 720 seconds. While conditions were photometric on this night, the seeing was rather inferior ($\sim 1.0''$ FWHM in K_s), providing limited utility in this crowded field.

2.2. CCD Observations

In order to accurately calibrate the astrometric reference frame of the IR images of GRS 1758-258, we obtained wide-field ($8' \times 8'$) CCD images of its field in the I band on June 29, 1998 using the Palomar 60-inch telescope. The total exposure time in each band was 300 seconds, and the typical stellar PSF had FWHM $\sim 1.2''$. We subtracted the CCD bias from each frame, divided by a flatfield, and interpolated over bad pixels and cosmic rays.

3. Astrometric Calibration of IR Images

3.1. 1E1740-2942

In the case of 1E1740-2942, we identified 4 stars in Figure 2 which are listed in the USNO-A2.0 astrometric catalog (Monet et al. 1998). One of them is a close double, which complicates the astrometry sufficiently that we dropped it from our analysis. We used the remaining 3 stars to determine the "best-fit" astrometric solution for Figure 2 and locate the radio position for 1E1740-2942 on Figure 2 (marked by an "X"). We use the VLA position $\alpha_{\rm J2000} = 17^h\ 43^m\ 54^s.83$ and $\delta_{\rm J2000} = -29^o\ 44'\ 42''.60$ (Marti et al. 2000). We then calculated the RMS residuals for the USNO star positions from this solution, which we find to be $\pm 0.37''$. Note that this includes the internal uncertainties in the USNO positions, which are typically $\sim 0.25''$. Including the 1σ uncertainties in the radio position ($0.1''$ – Rodríguez et al. (1992)) and in the radio-optical frame tie ($< 0.1''$ – da Silva Neto (et al.)), we arrive at a 90% positional uncertainty of $\pm 0.65''$. Figure 3 shows a section of Figure 2 close to the position of 1E1740-2942, including the 90% error circle. Comparison of this position to

similar results obtained independently by Marti et al. (2000) show a close match between them, to better than $\sim 0.2''$.

3.2. GRS 1758-258

In the case of GRS 1758-258, we could not identify any suitable USNO-A2.0 stars in the field of Figure 1, and thus turned to the larger-field CCD image as a secondary astrometric reference. We identified 12 USNO stars within $\sim 1.5'$ of the approximate radio position for GRS 1758-258. We use the VLA position $\alpha_{\rm J2000} = 18^h\ 01^m\ 12^s.395$ and $\delta_{\rm J2000} = -25^o\ 44'\ 35''.90$ (Mirabel & Rodríguez 1993). We then obtained an astrometric solution for the CCD image in this region using these stars. We then transferred these coordinates onto 5 stars near the position of GRS 1758-258 which were visible in both the I-band CCD image and the K-band NIRC image, and used them to derive a secondary astrometric solution for the NIRC image. The resulting position is indicated on Figure 1 by an "X". The RMS residuals to the CCD astrometric solution were $0.22''$, and the RMS residuals of the IR stars to the CCD solution were $\sim 0.06''$. Including the $0.1''$ 1σ uncertainties in both the radio position of GRS 1758-258 (Mirabel & Rodríguez 1993) and the optical-radio frame tie (da Silva Neto et al.), we obtain a 90% positional uncertainty of $0.50''$ for our position. Figure 4 shows a section of Figure 1 close to the position of GRS 1758-258, including the 90% error circle. Comparison of this position to similar results obtained independently by Marti et al. (1998) show a $\sim 1.5''$ offset between the two positions, which is large enough that the two 90% error circles just barely touch. The approximate location of the Marti et al. astrometric solution for GRS 1758-258 is also indicated in Figure 4.

4. Photometry of Candidates and Limits on Counterparts

4.1. 1E1740-2942

In Figure 3, we can see several stars near the position of 1E1740-2942, which we have identified by the numbering system introduced by Marti et al. (2000). We do not detect any objects other than the stars identified by Marti et al., nor do we fail to detect any objects identified by Marti et al. In addition, with our improved $0.45''$ angular resolution, we confirm the suggestion of Marti et al. (2000) that "Star 4" is an extended object. However, we cannot determine whether the extended appearance is due to truly diffuse emission or simply the overlap of several stellar images in this crowded field.

In Table 1, we present photometric results for the numbered stars in Figure 3, using FS28

as the photometric standard. This star has $m_K = 10.597$ mag and $m_H = 10.644$ mag, based on which we estimate $m_{Ks} = 10.62 \pm 0.03$ mag. Comparing the PSF-weighted photometry of the 5 images of FS28, we find an RMS variation of ± 0.02 mag in the measured flux levels. We performed photometry of the stars in the 1E1740-2942 field using the same PSF-weighted algorithm and assuming an average value for the sky background in the field. Due to the extreme crowding of the field, we find significant gradients in the apparent background level in this region of the field, and we estimate our uncertainty in the background level per pixel to be 20%. In addition, we include an estimated 10% uncertainty in the photometry due to transparency variations on these non-photometric nights.

All of the photometric results for the stars in Table 1 match the photometry of Marti et al. (2000) within the uncertainties, indicating that none of them varied significantly between June 1998 and May 1999. If we consider the exact center of our astrometric error circle for 1E1740-2942, we can place an upper limit on the presence of any stellar image of $m_{Ks} = 19.9$ mag at the 95% confidence level. Note that the noise in the image is dominated by pixel-to-pixel background variations which are repeatable between the individual subimages we combined to make Figure 3. This indicates that these variations are due to background gradients from the crowded field rather than photon statistics.

Due to the poor seeing of the April 1994 data, only Stars 1-3 are detectable, and Stars 1 and 2 are badly blended, preventing accurate photometry. However, by comparison with nearby field stars, we determine that Stars 1 and 3 did not vary by more than ~ 0.8 mag between April 1994 and June 1998. Furthermore, the non-detection of the other stars implies that they were all fainter than $K_s \sim 17.5$ mag in April 1994.

4.2. GRS1758-258

In Figure 4, we cannot detect any sources inside our error circle for GRS 1758-258. We do detect 3 stars near this position which were seen in I-band images by Marti et al. (1998) – labelled A, b, and c. Star A is the source identified as a candidate counterpart for GRS 1758-258 by Marti et al. (1998), and for which they obtained an infrared spectrum. We present photometry of these 3 stars in Table 2, following the same procedures described above for the field of 1E1740-2942. Note that our K_s-band photometry of Star A is $\sim 2\sigma$ brighter than the K-band photometry of Marti et al. (1998). While the two filters do differ somewhat, this is a heavily reddened star ($I - K = 5.0$ mag, according to Marti et al.), so we would expect the K_s-band flux to be *fainter* than the K-band flux. Thus, we have some marginal evidence for variability in Star A between 1994-1997 and June 1998. At the exact center of our astrometric solution for the position of GRS 1758-258, we can place an upper

limit on any stellar image of $m_{Ks} = 20.3$ mag at the 95% confidence level.

5. Discussion

5.1. 1E1740-2942

Our observations of 1E1740-2942 above essentially confirm those of Marti et al. (2000). We find virtually identical astrometric positions for the microquasar on the infrared sky, with the same candidates nearby, and very similar brightness for each of the candidates. The lack of apparent variability in the candidates, however, may indicate that none of them are in fact associated with the microquasar, given the known X-ray variability over the 1998-1999 time span (e.g. Main et al. (1999)).

The infrared extinction towards 1E1740-2942 is currently poorly constrained, but based on the estimated X-ray column density of $N_H \sim 0.5 - 1.0 \times 10^{23}$ cm^{-2} (Chen et al. 1994), we arrive at $A_{Ks} \sim 3.0 - 6.0$ mag. This in turn allows us to (very loosely) constrain the ranges of absolute magnitudes and thus spectral types for the stars in this field (see Table 1). As can be seen in Table 1, all of the 8 candidate counterparts in the field are consistent with both high-mass (early B or late O) main sequence stars, as well as low-mass (K-type) giants, for example. Thus, even if we choose to associate one of these candidates with 1E1740-2942, we unfortunately cannot place any interesting constraints on the nature of the binary system.

5.2. GRS1758-258

Our analysis of GRS 1758-258 presents two possible conclusions, depending on which astrometric calibration of its position is correct – the one we present above, or that of Marti et al. (1998). In the latter case, then Star A or one of the two stars near the "M" in Figure 4 is likely to be the IR counterpart to GRS 1758-258. Assuming $A_{Ks} = 0.9$ mag based on $N_H = 1.5 \pm 0.1 \times 10^{22}$ cm^{-2} from Mereghetti et al. (1997), and a distance of 8.5 kpc, we derive absolute magnitudes for the three stars of $K_s = -1.9, +1.35, +1.20$ mag, respectively. These are roughly consistent with an early K-type giant for Star A (as proposed by Marti et al. (1998)), and early A-type main sequence stars for the other two stars. Any of these is inconsistent with a high-mass binary companion scenario for GRS 1758-258, and instead indicates that the system is an intermediate- or low-mass binary.

However, as noted above, our own astrometric solution would rule out all three of these stars as counterparts to GRS 1758-258. Since our solution is based on and consistent with

the astrometric positioning of 12 USNO field stars with small internal scatter, the only possibility which would explain such a discrepancy is that the optical/radio frame tie is inaccurate for this region of sky at the $\sim 1''$ level. Since the USNO frame is tied to the International Coordinate Reference Frame via HIPPARCOS, with a claimed accuracy of < 1 mas (Perryman et al. 1997), this seems to be unlikely. Thus, we conclude that the error circle in Figure 4 is in fact the most accurate positional determination for GRS 1758-258.

In that case, the lack of an IR counterpart to $m_{Ks} > 20.6$ mag is particularly intriguing. Taking the same extinction and distance values as above, we place a limit on the absolute magnitude of any counterpart of $K_s > +4.9$ mag. This rules out any companion more luminous than a K7 main-sequence star. If this is correct, then GRS 1758-258 must be a (very) low-mass X-ray binary.

As a final alternative, it may be that the radio position is for some reason incorrect at the $\sim 1 - 2$ arcsecond level, which would leave several candidates for IR counterparts to GRS 1758-258.

6. Conclusions

We have presented deep infrared (2.2μm) imaging of the fields of the Galactic microquasars 1E1740-2942 and GRS 1758-258, along with astrometric positioning to the $\sim 0.5 - 0.6''$ level. We summarize our results as follows:

- For 1E1740-2942, our astrometric position agrees with that of Marti et al. (2000).
- We find all 8 candidate counterparts to 1E1740-2942 identified by Marti et al. (2000), and no new candidates.
- None of the candidate IR counterparts show significant variability from June 1998 to May 1999, while the X-rays from 1E1740-2942 *do* show variability over that epoch.
- For GRS 1758-258, our astrometric position, based on 12 nearby USNO reference stars, disagrees with that of Marti et al. (1998) by $\sim 1.5''$.
- We find no IR counterpart inside our 90% confidence level error circle down to a 3σ limit of $m_{Ks} > 20.3$ mag. For assumed $A_{Ks} = 0.9$ mag and $d = 8.5$ kpc, this limits any companion to be fainter than a main-sequence K5 star, implying that GRS 1758-258 is a low-mass binary.

- Alternately, if the astrometric position of Marti et al. (1998) is correct, we see only marginal evidence for variability from the brightest star in their error circle between June 1998 and the 1994-1997 photometry of Marti et al. (1998).

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Table 1. Photometry of Objects Near 1E1740-2942

Star Number	m_{Ks} (mag)	K_s (mag)[a]	Spectral Type[b]
1	17.1 ± 0.1	$-0.2 - -3.4$	B7V-B0V , K5III-G0III
2	18.2 ± 0.1	$+0.9 - -2.3$	A1V-B1V , K2III-G0III
3	16.8 ± 0.1	$-0.5 - -3.7$	B6V-O9V , K5III-G0III
4	18.2 ± 0.1	$+0.9 - -2.3$	A1V-B1V , K2III-G0III
5	18.7 ± 0.2	$+1.4 - -1.8$	A2V-B2V , K1III-G0III
6	19.1 ± 0.2	$+1.8 - -1.4$	A6V-B3V , G8III-G0III
7	19.1 ± 0.2	$+1.8 - -1.4$	A6V-B3V , G8III-G0III
8	19.5 ± 1.0	$+3.1 - -1.9$	G0V-B2V , K1III-G0III

[a]Assuming $A_{Ks} = 3 - 6$ mag and $d = 8.5$ kpc.

[b]Ranges given assuming luminosity class of III or V. All stars of luminosity class I are excluded.

Table 2. Photometry of Objects Near GRS 1758-258

Star Number	m_{Ks} (mag)	K_s (mag)[a]	Spectral Type
A	13.63 ± 0.13	-1.90	K0III
b	16.73 ± 0.16	$+1.35$	AOV
c	16.88 ± 0.16	$+1.20$	AOV

[a]Assuming $A_{Ks} = 0.9$ mag and $d = 8.5$ kpc.

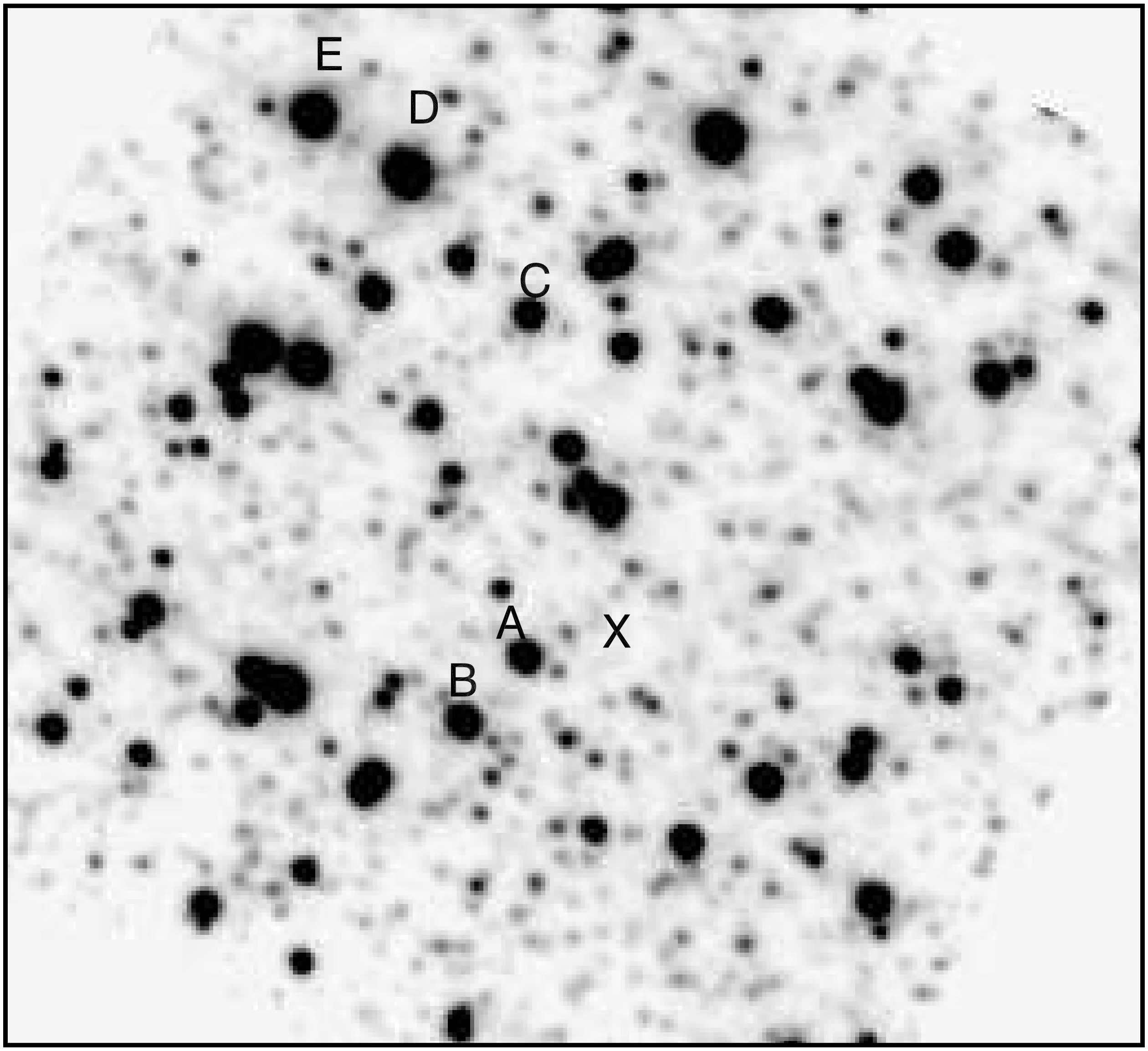

Fig. 1.— *Keck K_s-band image of the field of GRS 1758-258 (approximately 1′ on a side). "X" indicates the position of the microquasar. Letters indicates the stars visible in both the K-band and I-band CCD image used for astrometric calibration. North is up and east is to the left.*

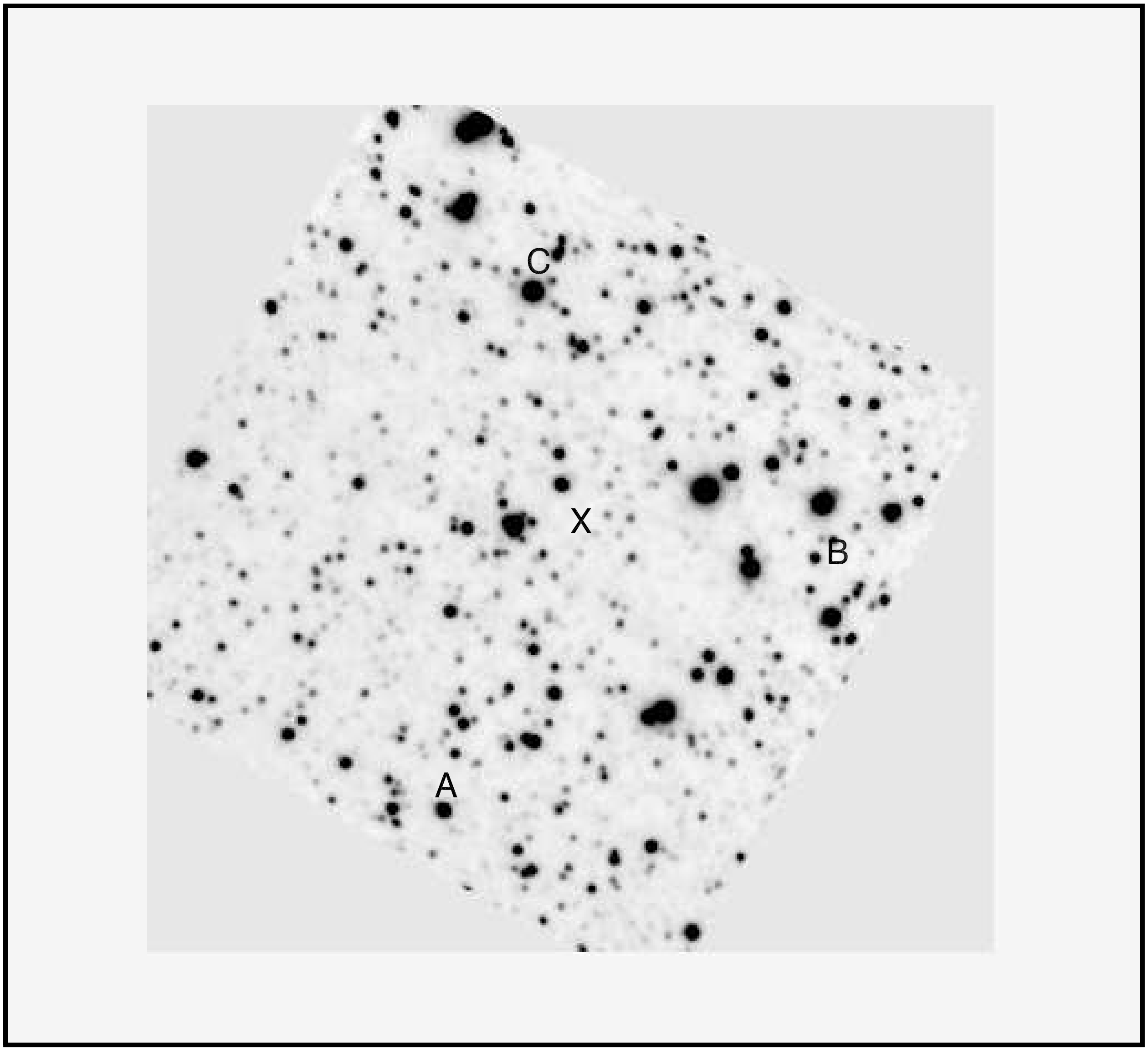

Fig. 2.— *Keck K_s-band image of the field of 1E1740-2942 (approximately $1'$ on a side). "X" indicates the position of the microquasar. "A", "B", and "C" are the USNO stars used for astrometric calibration of the image ("C" is the brightest star near the symbol). North is up and east is to the left.*

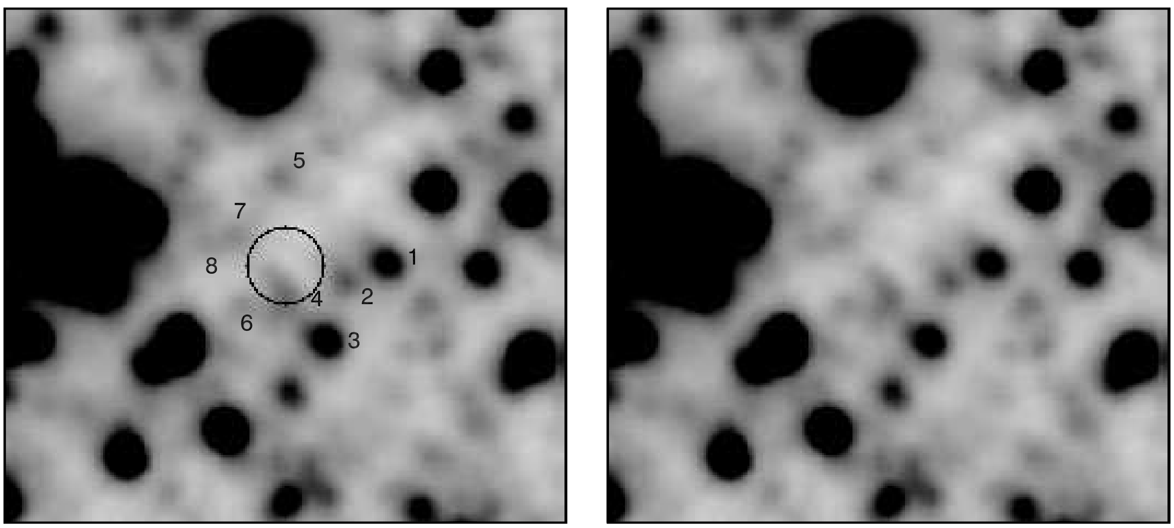

Fig. 3.— *Close-up* ($10'' \times 10''$) *Keck* K_s*-band image of the field of 1E1740-2942. The left side image shows the 90% error circle* ($1.3''$ *diameter) for the location of the microquasar, with numbers indicating the potential candidates reported by Marti et al. (2000). The right hand side is an identical copy of the image displayed without markings, for clarity.*

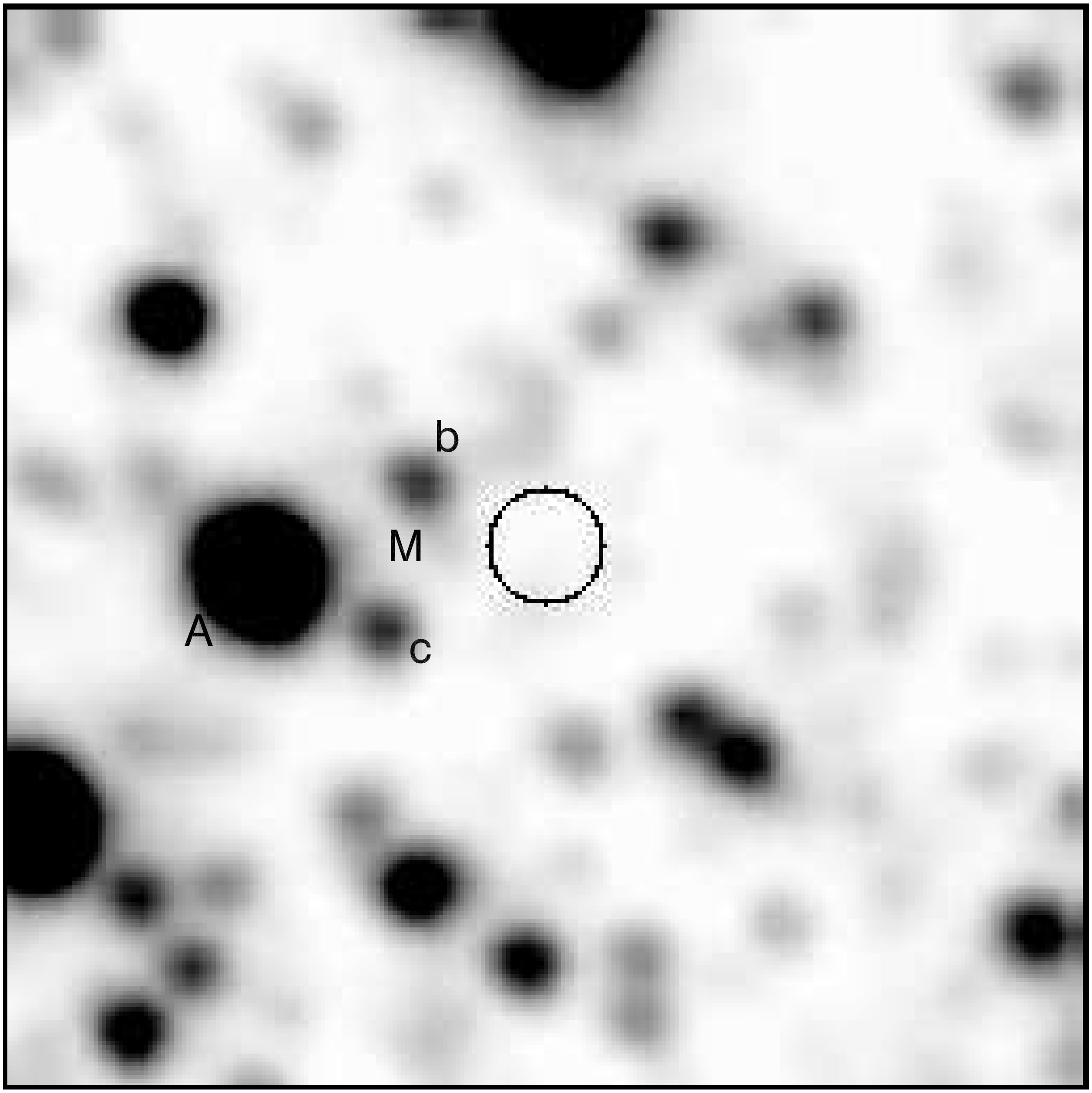

Fig. 4.— *Close-up ($10'' \times 10''$) Keck K_s-band image of the field of GRS 1758-258, including the 90% error circle ($1.0''$ diameter) for the microquasar position. "M" indicates the approximate position for the microquasar determined by Marti et al. (1998).*